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6. AUTHOR(S)
Jochen Klinke, Xin Xhang, Bernd Jahne

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California, San Diego
Scripps Institution of Oceanography
Physical Oceanography Research Division
9500 Gilman Drive
La Jolla, CA 92093-02

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13. ABSTRACT (*Maximum 200 words*)

This work is an extension of the early works on measuring short wind waves that have been funded by ONR for seven years. During this seven-year period, we have collected the only available systematic set of wave slope image data from different wind/wave facilities, and built a wave-imaging buoy that extends the capability of wave imaging to the field. Our objective for this extension is to complete a detailed analysis of the data obtained during the past seven years. Our findings are outlined as following: Current theories on short wind wave spectrum can qualitatively explain the spectral characteristics well, but can not quantitatively predict the measured spectra. The capillary wave spectrum dominated by parasitic capillaries (< 1 cm) is universal, or not sensitive to the tank geometry and wind fetch. The capillary-gravity waves (1-10 cm) are very sensitive to the tank geometry and wind fetch. Although we did not find the existence of pronounced bound waves which propagate at high speed, freely travelling short waves do propagate fast near long wave crests, and slowly near the troughs. We propose that speed modulation can affect the Doppler microwave return. Our suggestion fits well with new radar observation (Lamont-Smith 2000).

14. SUBJECT TERMS
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Upper Meter Processes: Short Wind, Waves, Surface Flow and Turbulence

Xin Zhang and Bernd Jähne
Scripps Institution of Oceanography, SIO-0213
University of California, San Diego, La Jolla, CA 92122
phone:(858) 534-7153 fax:(858) 534-8509 email:xzhang@ucsd.edu

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LONG-TERM GOALS

The long-range goal of this project is to advance the knowledge of small-scale air-sea interaction processes at the ocean surface. Our study is going to focus on the dynamics of short wind-waves, the surface flow field and micro turbulence. This includes both the basic knowledge of these processes as well as their implications for radar remote sensing

OBJECTIVES

This work has been funded by ONR for seven years. During this period we have collected the only available systematic set of wave slope image data from wind/wave facilities including Delft, Marseilles, Heidelberg, Scripps, and Wallops facilities, and built a wave-imaging buoy that extends the capability of wave imaging to the field. Our objective for this extension is to complete a detailed analysis of the data obtained during the past seven years. The emphasis includes the following:

1. Statistical wave slope data such as 2-D slope probability density functions and mean square slopes, with special attention to the high slopes because of their importance for radar imaging.
2. Directional wavenumber-frequency spectra from image sequences.
3. Determination of phase speeds and phase modulation.

It is intended to make these data on CD-ROMs and/or the internet so it is available for any interested researcher.

APPROACH

The slope image data that we have are collected under different wind wave facilities. This enable us to compare short wind wave statistics among different fetches and wind channel geometry.

WORK COMPLETED

We have complete the works on 1)Wavenumber spectra of short wind waves, and 2)Determination of propagation of short wind waves.

RESULTS

A. Shape of the spectra

To illustrate the general characteristics of the wave spectra for the full wavenumber range, omni-directional saturation spectra B(k) (that is the directional wave slope spectra integrated over all wave propagation directions and scaled with k^2 are shown for the different wind speeds in the figure 1. Generally, we find a local maximum of the spectral level at a wavenumber of k -800-1000 rad/m and a fast drop of the spectral level at high wavenumbers. These main features of our measured spectra are reproduced by the model of Kudryavtsev et al (1999) qualitatively. However, the spectral dip and cut-off are over-estimated by their model.

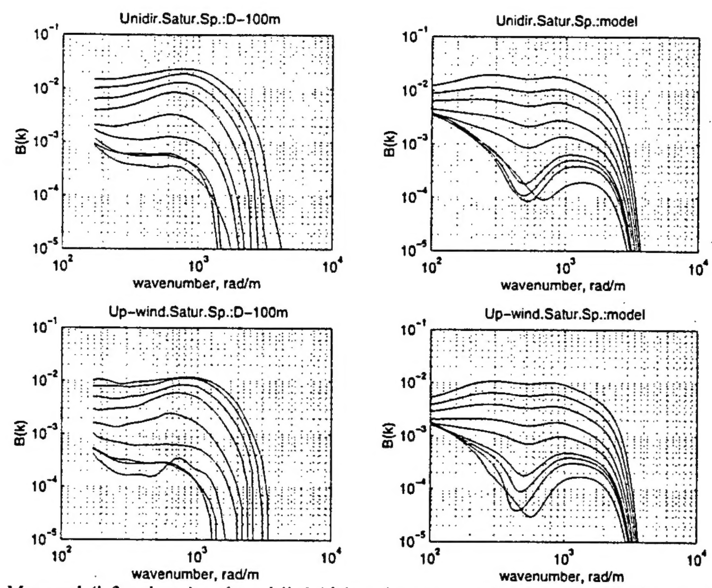

Figure 1 Measured (left column) and modelled (right column) saturation spectra. Omnidirectional spectra - upper panel, up-wind spectra – lower panel. Spectra relate to the friction velocity 0.09, 0.11, 0.12, 0.13, 0.17, 0.22, 0.31, 0.42, 0.59 m/s (lines from the bottom to the top). Delft facility, fetch 100 m.

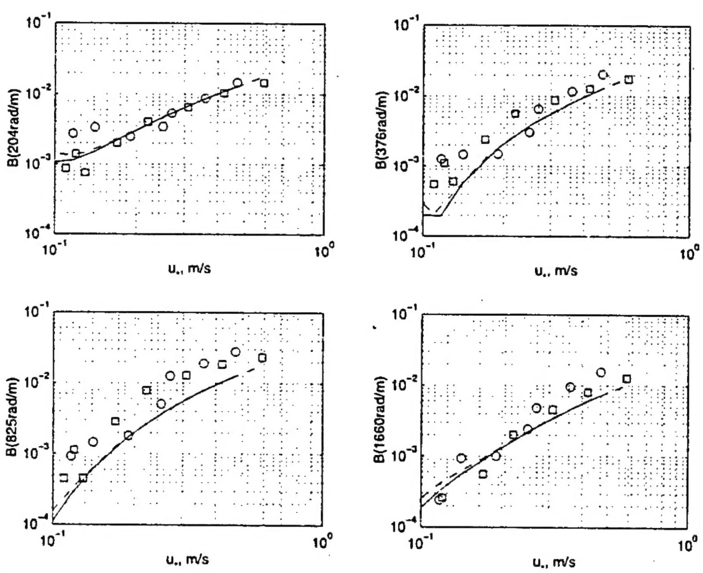

Figure 2. Wind speed dependence of the up-wind saturation spectra at different wavenumber (indicated on the plot) for long fetch conditions. Open circle - measurements at Heidelberg circular facility, infinite fetch, open square - measurements at Delft facility, fetch 100 m. Solid line – model results, simulation of Heidelberg experiment, dashed line - model results, simulation of Delft experiment.

B). Spectral wind dependency

Figure 2 shows the wind speed dependence of the up-wind and omnidirectional, measured and modelled saturation spectra at the given wavenumber of 204 rad/m, 376 rad/m, 825 rad/m, and 1660 rad/m for long fetch conditions (Delft facility, fetch of 100m and Heidelberg circular facility). We first notice that the data obtained in the facilities of different geometry are in an agreement with each other. In the vicinity of the minimum phase velocity (k = 374 rad/m) and at longer waves (k= 204 rad/m), saturation spectra are

proportional to u_*^2. In the capillary range saturation spectra are proportional to u_*^3 for low wind speeds. For high wind speeds, $B \propto u_*^{0.3}$. The model results shown in the same figures are in a qualitative agreement with our observations.

C) Spectral angular spreading

The angular spreadings of measured spectra at the given wavenumber of 204 rad/m, 376 rad/m, 825 rad/m, and 1660 rad/m for long fetch conditions (Delft facility, fetch of 100m and Heidelberg circular facility) are shown in figure 3. Apart from the lowest wind speeds, the angular parameter increases with an increase of the friction velocity, i.e. the angular spreading of waves tends to be broader if the wind speed is increasing. The experimental estimates show that the angular spreading of waves in the laboratory is far from being isotropic.

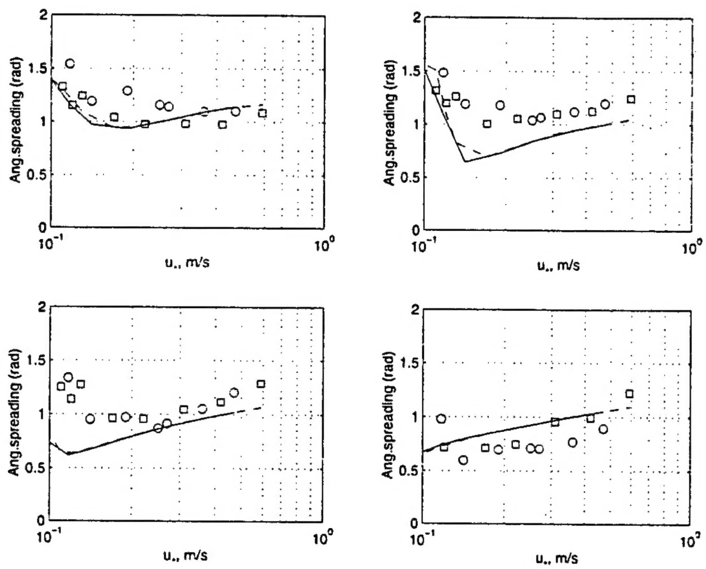

Figure 3. Angular spreading dependence on the wind speed at different wavenumber (indicated on the plot). Open circle - measurements at Heidelberg circular facility, infinite fetch, open square - measurements at Delft facility, fetch 100 m. Solid line - model results, simulation of Heidelberg experiment, dashed line - model results, simulation of Delft experiment.

D) Propagation of short waves

Examples of the ensemble averaged propagation speeds of short wind waves estimated from surface slope images are shown here in figure 4. The calculations by wavelet tracking (circles) and cross-correlation (solid dots) are consistent. In figure 4, it only shows the propagation speeds in the direction of the wind. The propagation speeds in other directions have similar features, but the offset from the dispersion relation (solid curves) approaches to zero towards the cross-wind direction which is reasonable (no mean current in the across-wind direction). The coherence (dash-dot-dash curves) reduces at the high wave number, and decreases more rapidly with the increasing wind speed. The propagation speeds of short waves apparently vary with wave length, indicating that they are dispersive in average.

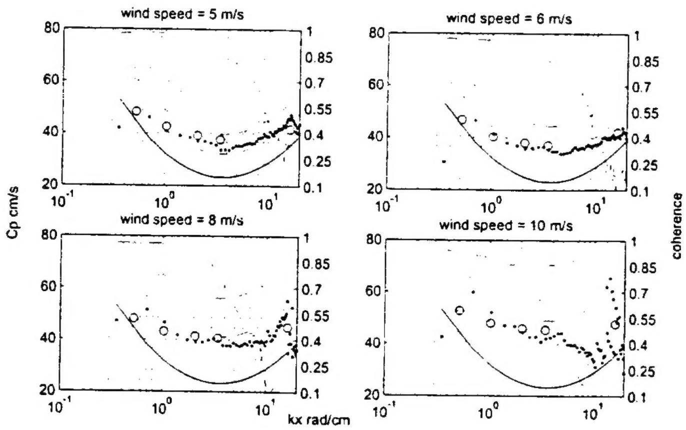

Figure 4 The propagation speeds of different wave components in the wind direction. Image data are from an experiment at the wind wave facility at the University of Heidelberg. Solid dots and open circles are data points of propagation estimations from cross-correlation and wavelet tracking respectively. Solid curves are dispersion relation for free waves. Dash-dot-dash curves are the coherence. The top dashed curve is the linear phase velocity plus $0.55u_*$. The bottom dashed curve is the linear phase velocity plus $0.30u_*$.

E) Surface currents

Waves of different lengths are affected by the surface currents to the different depths. The surface drift current profiles are thus further estimated from the differences between wave propagation speed and the phase speed of different wavelength. Examples are shown in figure 5. The surface wave can be used as natural traces to detect surface currents which, otherwise, is very difficult to obtain.

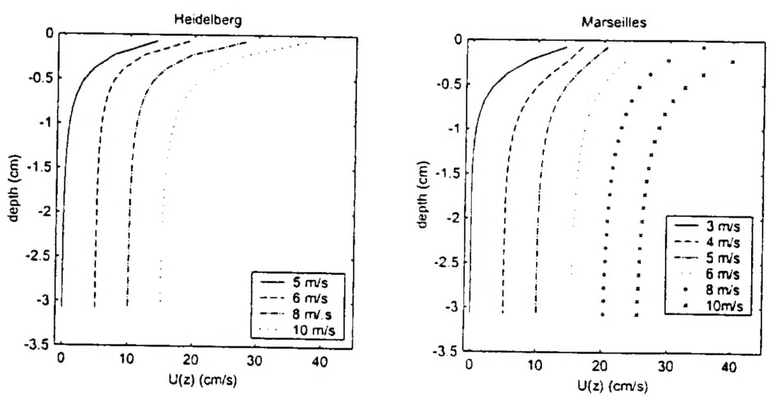

Figure 5 Surface shear currents at different wind conditions and different wind wave tanks. The velocity profiles are inverted from measured propagation speed of short wind waves.

F) Microwave sea return

Due to the long wave orbital advection, the propagation speeds of short waves are unevenly distributed on the different phases of the underlying long waves, faster near the long wave crests and slower near the troughs. The modulation of short wave speeds is depended on the short wave length under the same long wave conditions. The apparent short gravity wave speed is approximated at first order of AK as:

$$c = \frac{f}{k} = \bar{c}_p\left(1 + \left(\frac{C}{\bar{c}_p} - 1\right) AK\cos(\psi)\right)$$

The modulation is a function of ratio of the phase speed of the underlining long wave and the averaged phase speed of the short gravity train, and it increases as the waves get short. The modulation for gravity-capillary waves can be calculated , however, an explicit neat expression is difficult to find. The tendency of the modulation can be understood by looking at very short waves, pure capillary waves:

$$c=\frac{f}{k}=\bar{c}_p\left(\frac{\sigma}{\bar{\sigma}}\right)^{\frac{1}{3}}\left(1+\left(\frac{\bar{\sigma}}{\sigma}\right)^{\frac{1}{3}}\frac{C}{\bar{c}_p}AK\cos(\psi)\right)$$

The apparent phase speed modulation is dependent on both $\beta=\frac{C}{\bar{c}_p}$ and $\left(\frac{\bar{\sigma}}{\sigma}\right)^{\frac{1}{3}}$. The factor of $\left(\frac{\bar{\sigma}}{\sigma}\right)^{\frac{1}{3}}$ is the contribution from modulation of the intrinsic frequency of the short wave, which is not important for pure gravity waves. It can be shown :

$$\left(\frac{\bar{\sigma}}{\sigma}\right)^{\frac{1}{3}}\sim 1+h\left(\frac{C}{\bar{c}_p}\right)AK\cos(\psi)$$

Here, $h\left(\frac{C}{\bar{c}_p}\right)$ is an order O(1) quantity. For example, h=-1, when $\frac{C}{\bar{c}_p}=1$, h=0, when $\frac{C}{\bar{c}_p}=0$, and h=1/2, when $\frac{C}{\bar{c}_p}=\infty$. Since capillary wave speed, $\bar{c}$, increases with the wavenumber, hence, redeces the ratio $\frac{C}{\bar{c}_p}$, which leads to a decrease in the modulation of apparent propagation phase speed. Although we did not find the existence of pronounced bound waves which propagate at high speed, freely travelling short waves do propagate fast near long wave crests, and slowly near the troughs. We propose that speed modulation can affect the Doppler microwave return in the laboratory tanks based on the basic idea of composite surface scattering theory (Plant 1997).

The basic difference in propagation of bound waves and modulated free short waves is the bound wave speed does not change with wavelength while the modulation of free short waves is depend on their wavelengths. One would expect that Doppler frequency due to bound waves is uniform for the different radar frequencies whereas the Doppler frequency due to modulated free waves changes with the radar frequencies. Lamont-Smith (2000) has recently shown measurements of Doppler spectra of laboratory wind waves at large incident angle (84°). Eight radar frequencies over a range from 3 GHz to 94 GHz have been used. It is equivalent to surface waves from 4.6 cm to .14 cm. From his result (figure 14), the slow scatters (VV return) follow the wave dispersion closely if the surface wind drift is included, and the mean speed of fast scatters increases towards the maximum at about 2 cm wavelength and then decreases towards higher wavenumber. This fits well with our suggestion that the modulation of short wind wave speed should be accounted for the major contribution to the Doppler frequency shift of radar return from laboratory wind waves.

IMPACT/APPLICATIONS

1)The lack of bound waves at high wind speeds lead us to suggest a different model of microwave backscatter at large incident angles. Due to the long wave orbital advection, short wind waves propagate faster near the long wave crests and slower near the troughs. These short wind waves can account for the fast and slow scatterers in microwave Doppler return of some laboratory wind-wave measurements (at least when waves are not extremely steep and breaking is not very frequent). The model can explain well the frequency-dependency of Doppler shift of radar return (Lamont-Smith 2000), while other models cannot explain. This also implies that the difference of the fast and slow scatterers can be used as an indicator of the steepness of underlying long waves. This can be valuable since it can be measured remotely.

2)The mean propagation speed measured is larger than the linear wave speed by a few percent of the wind speed, the same order magnitude of the surface drift (wind drift and Stokes drift). The surface currents at different depths affect waves of different lengths. Reasonable shear profiles are estimated from the differences between wave propagation speed and the phase speed of different wavelength. The fact that surface currents are not over estimated further supports our assessment that the contribution to the averaged wave propagation from bound waves is not substantial. This shows a potential application of using surface waves as natural traces for detecting surface current which, otherwise, is very difficult to obtain especially in the fields.

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Plant, W.J. 1997 A model for microwave Doppler sea return at high incidence angles: Bragg scattering from bound, tilted waves. *J. Geophys. Res.* **102**, 21131-21146.

RELATED PROJECTS

This work is closely related to our studies of sea surface micro-structure with support from ONR (N000-14-99-1-0191). That work has been focused on the field measurements of sea surface. We have deployed instrumentation to collect data in exercises off San Diego. The other related study is on impact of ripples on short wave dissipation (NSF).

PUBLICATIONS

Klinke, J., B. Jähne, and S. R. Long 2000 Observations of free and bound gravity-capillary waves, pp87-88

Zhang, X., J. Klinke and B. Jähne 2000 A study of advection of short wind waves by long waves from surface slope images pp93-100

Engelmann, D., C. Garbe, M. Stöhr and B. Jähne Three dimensional flow dynamics beneath the air-water interface pp181-186

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Klinke and S. R. Long 2000 Generation of Short Waves by Wave-Current Interaction, IGARSS 2000

Klinke, K., V. N. Kudryavtsevz, V. K. Makin and B. Jähne 2001 Wavenumber Spectra of Short Wind Waves: Laboratory Measurements and Interpretation, IGARSS 2001

Zhang, X. 2002 Propagation properties of laboratory short wind waves inferred from surface slope images, submitted to JFM

Klinke, K., V. N. Kudryavtsevz, V. K. Makin and B. Jähne 2002 Wavenumber Spectra of Short Wind Waves: Laboratory Measurements and Interpretation, in preparation for submission to JPO